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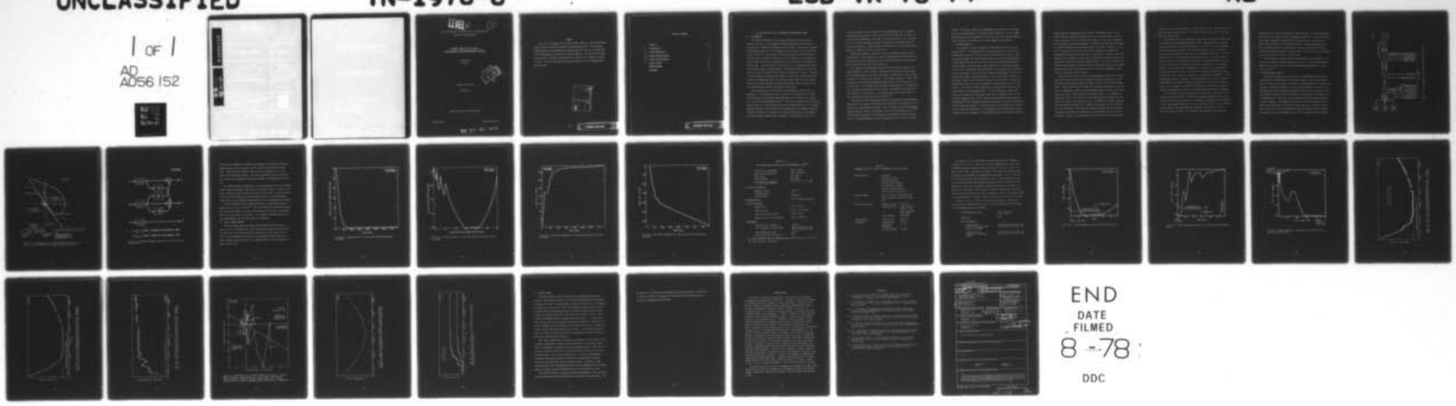

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FLIGHT RESULTS OF LES-8 AUTONOMOUS STATIONKEEPING SYSTEM

S. SRIVASTAVA

Group 69

TECHNICAL NOTE 1978-8

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LEXINGTON MASSACHUSETTS

ABSTRACT

This note is a summary of the initial flight results of the Lincoln Experimental Satellite 8 (LES-8) autonomous stationkeeping system. The autonomous stationkeeping system on LES-8 was activated between 7 July and 4 October 1976 for stationkeeping the satellite at 109.7°W longitude. The satellite acquired station without overshoot and maintained the station with an absolute accuracy of 0.06°. The fuel efficiency during this experiment in the overdamped mode was about 50%.

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FLIGHT RESULTS OF LES-8 AUTONOMOUS STATIONKEEPING SYSTEM

I. INTRODUCTION

The LES-8/9 satellites have autonomous three-axis attitude-control systems. Each has a single gimballed momentum wheel and two scanning IR Earth sensors to measure the satellite pitch and roll. The satellite attitude is maintained within 0.1° of the nominal on the pitch and roll axes and 0.6° on the yaw axis.[1] The circular, synchronous, satellite orbits are almost coplanar with the plane of the Ecliptic. The satellites are not geostationary, but appear to move 25° north and south of the Equator with a period of a sidereal day. The ground trace of each satellite in a synchronous, circular orbit repeats itself in a figure-eight. The average longitude of the ground trace over a day is defined as the satellite's location or station. The satellites are, however, stationary with respect to each other, except when either or both are changing stations. For orbits of small eccentricity the ground traces will be distorted from the ideal figure-eight, and the satellites may have small periodic motions with respect to each other.

The geosynchronism of the satellite is disturbed by various orbit perturbations. The perturbations of the satellites are largely due to the non-spherical shape and non-uniform mass distribution of the Earth; this results in a non-central gravitational field.[2] The other perturbations at synchronous-orbit are due to the gravitational fields of the Moon and the Sun,[3] the solar-radiation pressure, and reactions due to thermal and electromagnetic radiation from the satellites. To counteract the above perturbations a geosynchronous satellite requires periodic orbit corrections. The frequency of the orbit

corrections depends on the accuracy of stationkeeping required; for example, a stationkeeping accuracy of ±0.2° may require corrections every 30 days. In conventional stationkeeping it is usual to track the satellite over a period of one or two days, determine its orbit, and compute the thrusting time for each orbit correction. Each thrusting is followed up with another orbit determination to evaluate its effect on the orbit.

LES-8/9 are designed to maintain a station autonomously without ground interventions. Station changes are done by transmitting the information about the new station to the satellite; on receiving this information the satellite moves towards the new station and acquires it.

The autonomous stationkeeping system on these satellites consists of an IR Earth sensor for pitch (azimuth) sensing, two Sun-transit azimuth sensors, an Earth-shadow sensor, navigation electronics, a high-accuracy clock, a digital filter, a controller and thrusters. The thrusters comprise a central cold-gas ammonia system with stationkeeping nozzles on the east and west faces of the satellite. The autonomous stationkeeping system operates in a closed loop; the loop between the thrusters and the input to the sensors is closed by the orbit dynamics of the satellite. The thruster modifies the orbit, which in turn determines the new inputs to the sensors.[4]

The design of the stationkeeping system was done using a digital-computer simulation of the sensors, the electronics, the dynamics and kinematics of the orbit, and a satellite-attitude model. The final design of the stationkeeping system takes into account the stochastic nature of the navigation error.[4,5] The design and parameters of the system are optimized for various navigation errors. The stationkeeping accuracy is designed to be ±0.15° from a desired

station. The station change can be commanded at all rates up to ±2.5°/day. This rate is constrained by the maximum-thrust limitations, the fuel budget, and other operational requirements of the satellites. The coasting speed between stations can be selected by a single command from the ground.

II. SYSTEM DESCRIPTION

The satellite's orbital longitude is determined on-board by its navigation logic.[5] In the primary mode, the navigation system uses two Sun-azimuth-transit sensors[6] located such that Sun transits are seen by these two sensors whenever the Sun-to-Earth-to-satellite lines form approximately a right angle (6 AM and 6 PM local time along the sub-satellite meridian). The deviations in the Sun-transit times from those for right-angle geometry are due to the eccentricity and inclination of the orbit and to the satellite attitude excursions. The pitch and roll angles are measured by a pair of infrared Earth sensors (horizon scanners). The yaw angle does not affect the Sun-transit times at the two chosen locations (6 AM and 6 PM). The roll excursion has a small effect for a satellite in near-ecliptic orbit and is neglected. The effects of pitch excursions on the Sun-transit times are taken into account in the navigation logic. It is also necessary to take into account the variation in Sun-transit time due to non-uniform motion of the satellite around the Sun. This is done by using an on-board solar-ephemeris synthesizer;[7] this synthesizer generates the angular corrections required at every one-half-day interval. The corrections can be synthesized for circular orbits of various inclinations. The inclination, the ascending node and the starting time are programmed in the synthesizer and can be altered in orbit by

transmitting the information from the ground. The angular errors in Sun-transit geometry resulting from the eccentricity of the satellite orbit are equal and opposite for the 6 AM and 6 PM transits, so they can be eliminated by averaging two successive measurements. Similarly the small solar parallaxes are equal and opposite at two opposing points in an orbit. Therefore, errors due to eccentricity of the orbit and to solar parallax are eliminated by averaging the observations on two sides of the orbit in a digital filter. The navigation logic compares the Sun-transit times with 12-hour clock pulses generated from a stabilized on-board frequency source. The satellite station is calculated from the phase of the Sun-transit times with respect to the 12-hour stationkeeping clock. The desired station is changed by commanding a phase change of this clock from the ground.

Since the orbit planes of the Lincoln Experimental Satellites 8 and 9 are near-ecliptic, the satellites pass through the Earth's shadow once per day. The times of entering and leaving the shadow are detected by an Earth-shadow sensor. These times are used to compute the longitude independent of the Sun-transit measurements; therefore the Earth-shadow sensor is used in the backup navigation system. When using the Earth-shadow sensor, it is necessary to compare the times of the satellite's crossing the middle of shadow (once per day) with a 24-hour stationkeeping clock. The middle of the shadow cannot be observed directly; therefore it is computed by observing times of entry and exit from the shadow. Since the path through the shadow does not depend on the satellite attitude, the observations are not dependent on the attitude excursions. However, a single observation every orbit does not allow compen-

sating the error due to eccentricity of the satellite orbit. This results in a small periodic station drift of the satellite (with a full period of one year) when this mode is used.

The navigation error in computing the longitude is therefore caused by the inaccuracies in attitude determination and their compensation when using the Sun-transit sensors, and by the eccentricity of the orbit in the back-up mode using the Earth-shadow sensor. Small additional errors result from drifts in the sensors and the inaccuracies of the solar-ephemeris synthesizer. The navigation error due to attitude excursions and sensor drift is mostly random in nature; therefore it is necessary to filter the longitude measurement to compute the drift and drift rate of the satellite with respect to the assigned station. The filtering also accomplishes the averaging of the measurements at 6 AM and 6 PM Sun transits. The filter is linear time-varying and can be selected to operate either in an eighth- or a sixteenth-order mode.[4] In the eighth-order mode the filtering is performed on batches of eight consecutive measurements, and computed variables are updated after every fourth measurement. In the sixteenth-order mode the filtering is performed on sixteen consecutive measurements and outputs are updated after every eighth measurement.

The controller used for computing the thrusting time is non-linear, with switching and dead zones.[4] The thrusting constant, damping constant and coasting speed of the controller can be changed by command and can be adjusted to give the optimum performance for a given navigation error. The cold-ammonia gas thrusters of the satellites have selectable thrust (force) levels of 88 μ-lb, 1m-lb, and 2m-lb. The autonomous stationkeeping system uses the

low-thrust level of 88 μ-lb; during the system operation, the thrusting duration and direction are changed by the stationkeeping controller. In the Sun-transit-sensor mode, longitude is computed every one-half day and the thrusting is done every one-half day for a computed duration. In the Earth-shadow-sensor mode, although longitude is computed once every day, thrusting is initiated at every one-half day interval. This was done to avoid building up eccentricity due to thrusting on one side of the orbit only.

A block diagram of the autonomous stationkeeping system is shown in Fig. II-1 and a controller diagram is shown in Fig. II-2. The linearized dynamical model of the satellite, used for the stationkeeping-system design, is shown in Fig. II-3.[4]

III. GROUND TESTING RESULTS

The design and functional verification of the autonomous stationkeeping system was done by open-loop and closed-loop testing. In the open-loop testing, the outputs of the system in response to a predetermined set of inputs were observed. Closed-loop testing of the system was performed to study the system performance for various orbits, perturbations, sensor noises, navigation errors and attitude excursions. For the closed-loop testing, the orbit dynamics and its perturbations, navigation errors and attitude excursions were simulated on a digital computer. The computer was linked with the stationkeeping system both at the sensor-input end and the thruster-output end. Thrusters were not used in this test; only the thrusting duration was monitored by the computer. The computer, in turn, computed a new set of orbit parameters, which together

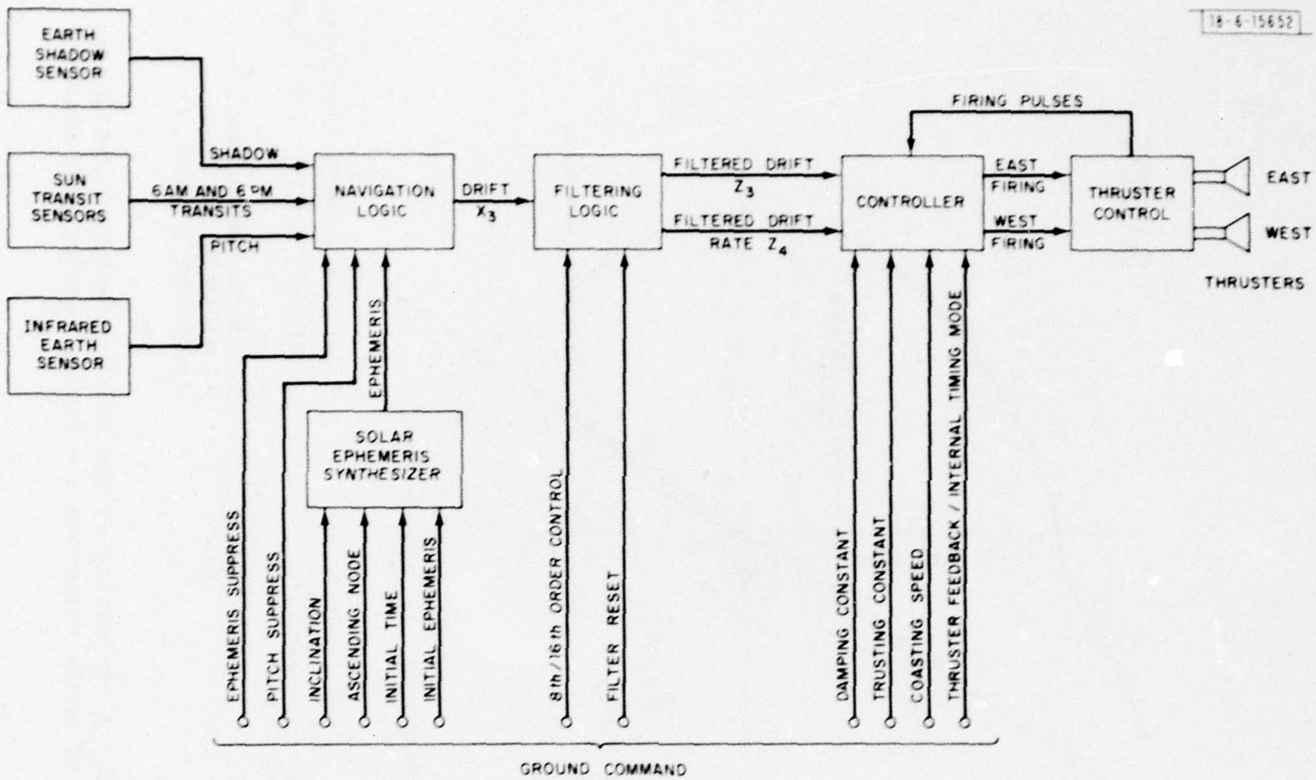

Fig. II-1. Block diagram of the LES-8/9 stationkeeping system.

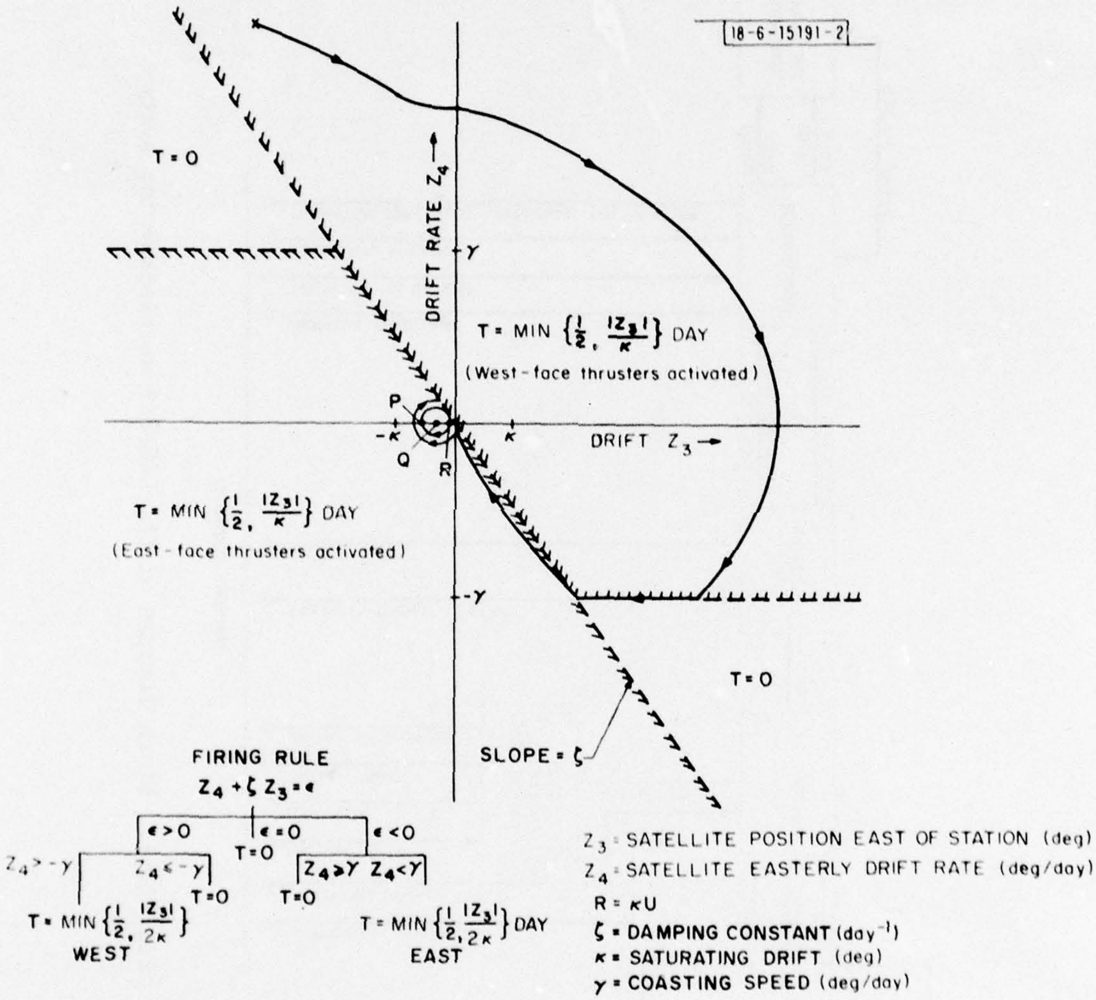

Fig. II-2. A trajectory of the stationkeeping controller in the presence of small noise and a constant secular perturbation.

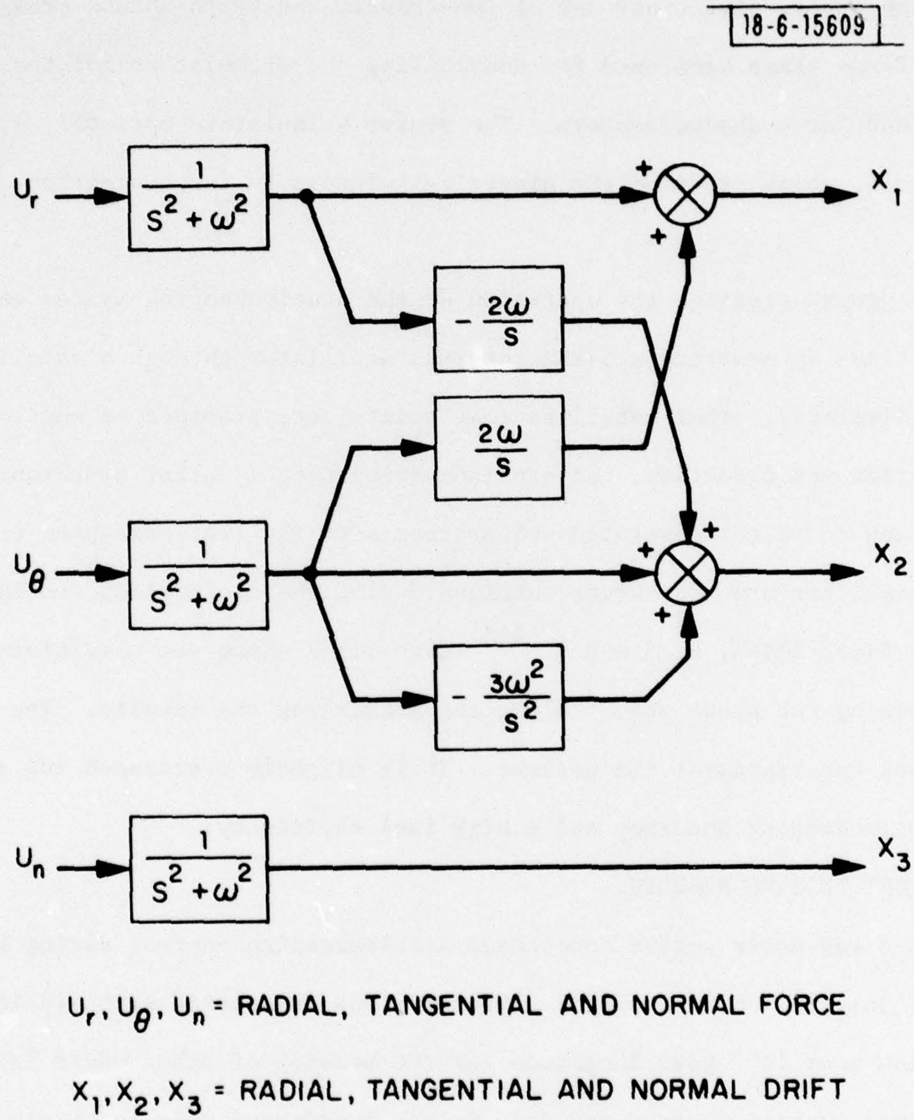

Fig. II-3. Linearized dynamical model for a satellite in near-circular orbit.

with the orbit kinematics (including solar ephemeris), satellite attitude and navigation error, give a new set of Sun-transit and Earth-shadow-crossing times. These times were used for controlling the stimulators for the Sun-transit and Earth-shadow sensors. The sensor stimulators optically actuated the sensors, which provided the electrical signals to the navigation electronics.

For ground-testing, the operation of the stationkeeping system was speeded up 6250 times by powering a 5-MHz internal oscillator through a satellite test point. Similarly, other satellite test points were provided to monitor thrusting duration and direction, the stationkeeping clocks, other synchronizing clocks, and to inject simulated sensor inputs to the stationkeeping electronics.

Typical performance curves obtained during the closed-loop testing are shown in Figs. III-1, 2, 3 and 4.[8] Table III-A shows the conditions assumed for obtaining the above set of plots and summarizes the results. The response shown does not represent the optimum. It is slightly overdamped and shows a good stationkeeping accuracy and a high fuel efficiency.

IV. FLIGHT TESTING RESULTS

LES-8 was under active autonomous stationkeeping control during the period 7 July to 4 October 1976. This test was associated with placing LES-8 on station near 110° west longitude for the benefit of other users late in 1976. This experimentation was done in the overdamped mode to obtain transient response without overshoot. The conditions used for this experiment are given in Table IV-A.

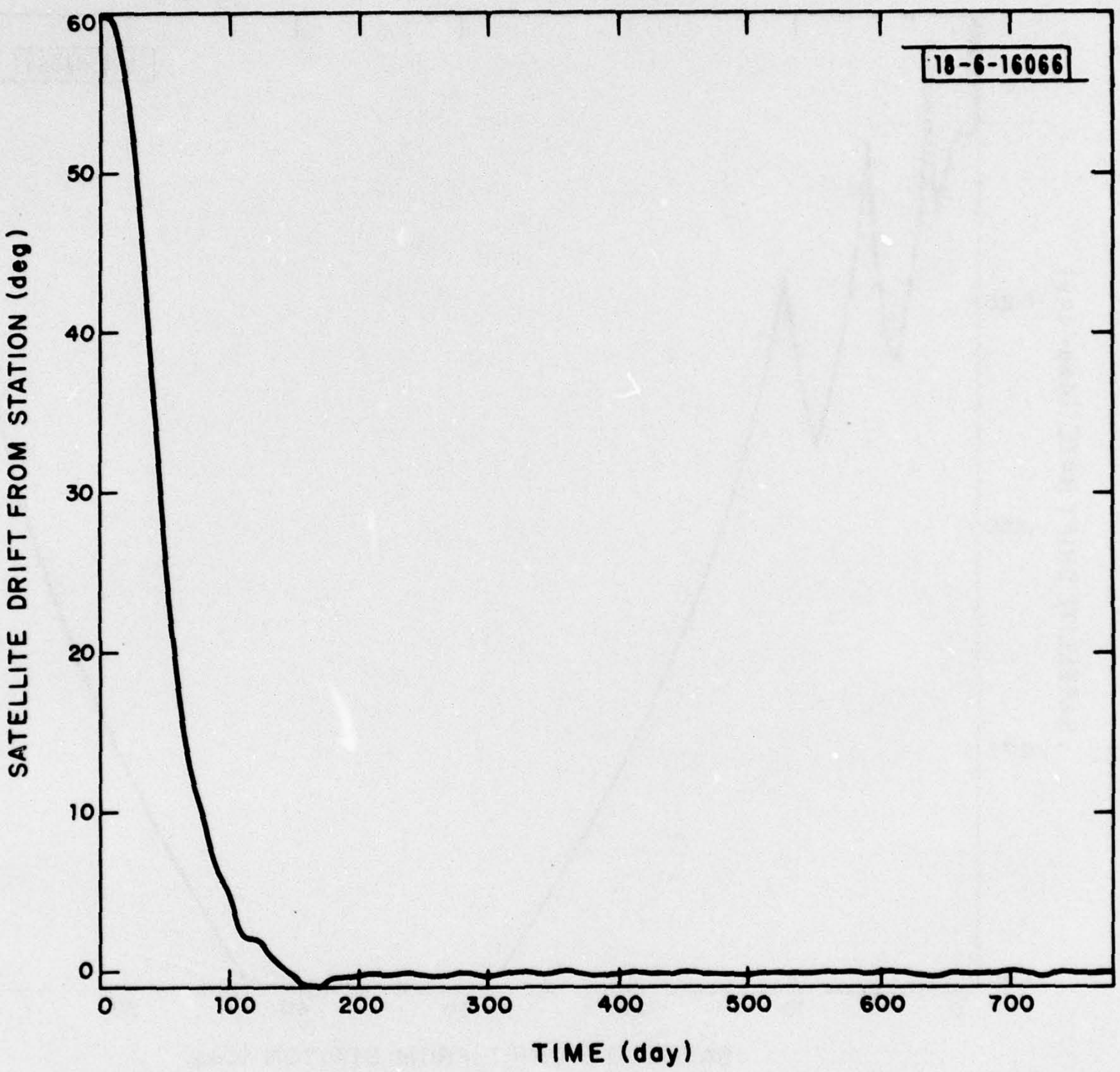

Fig. III-1. Satellite drift vs. time during closed-loop testing on ground.

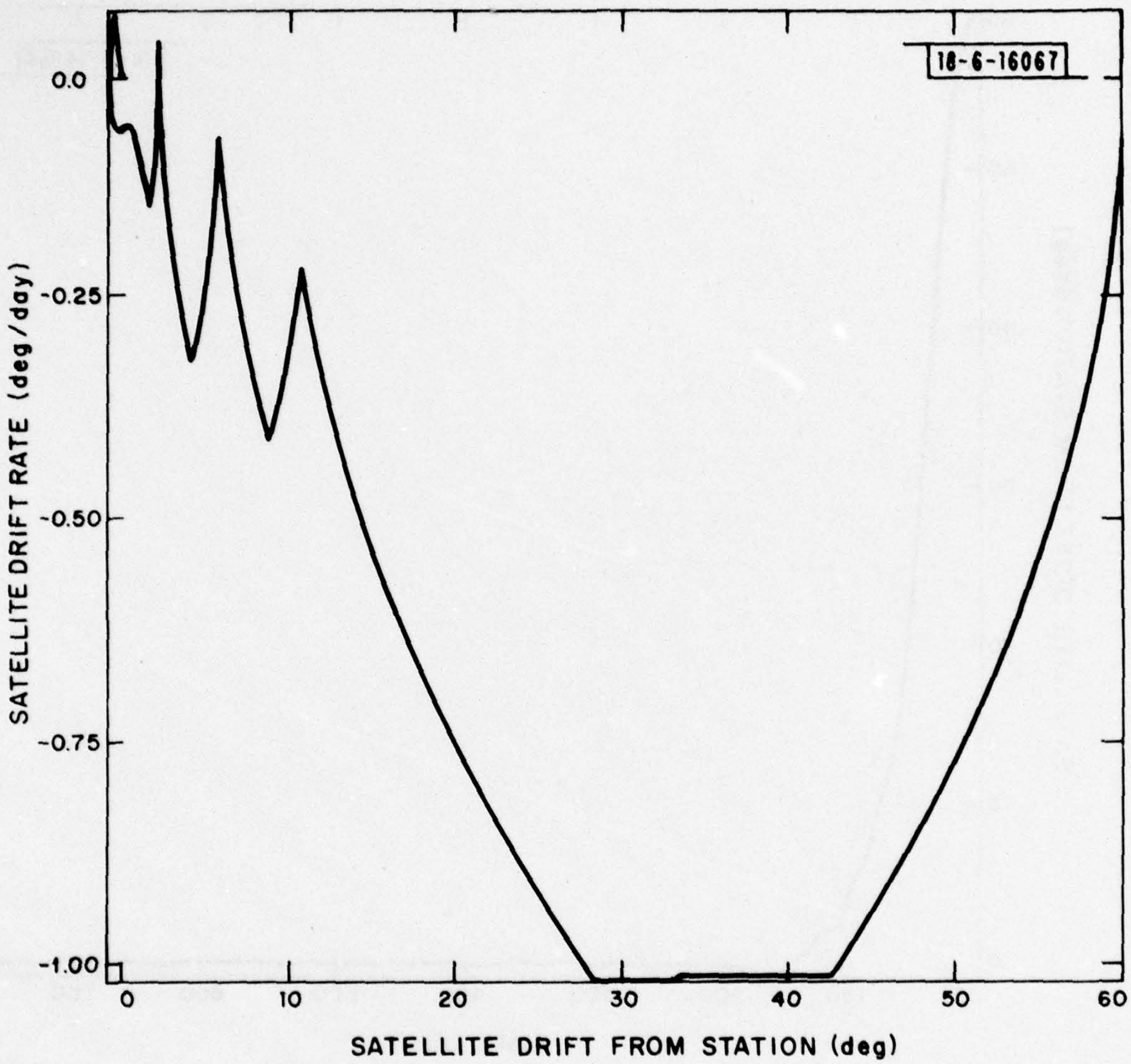

Fig. III-2. Satellite drift vs. drift rate during closed-loop testing on ground.

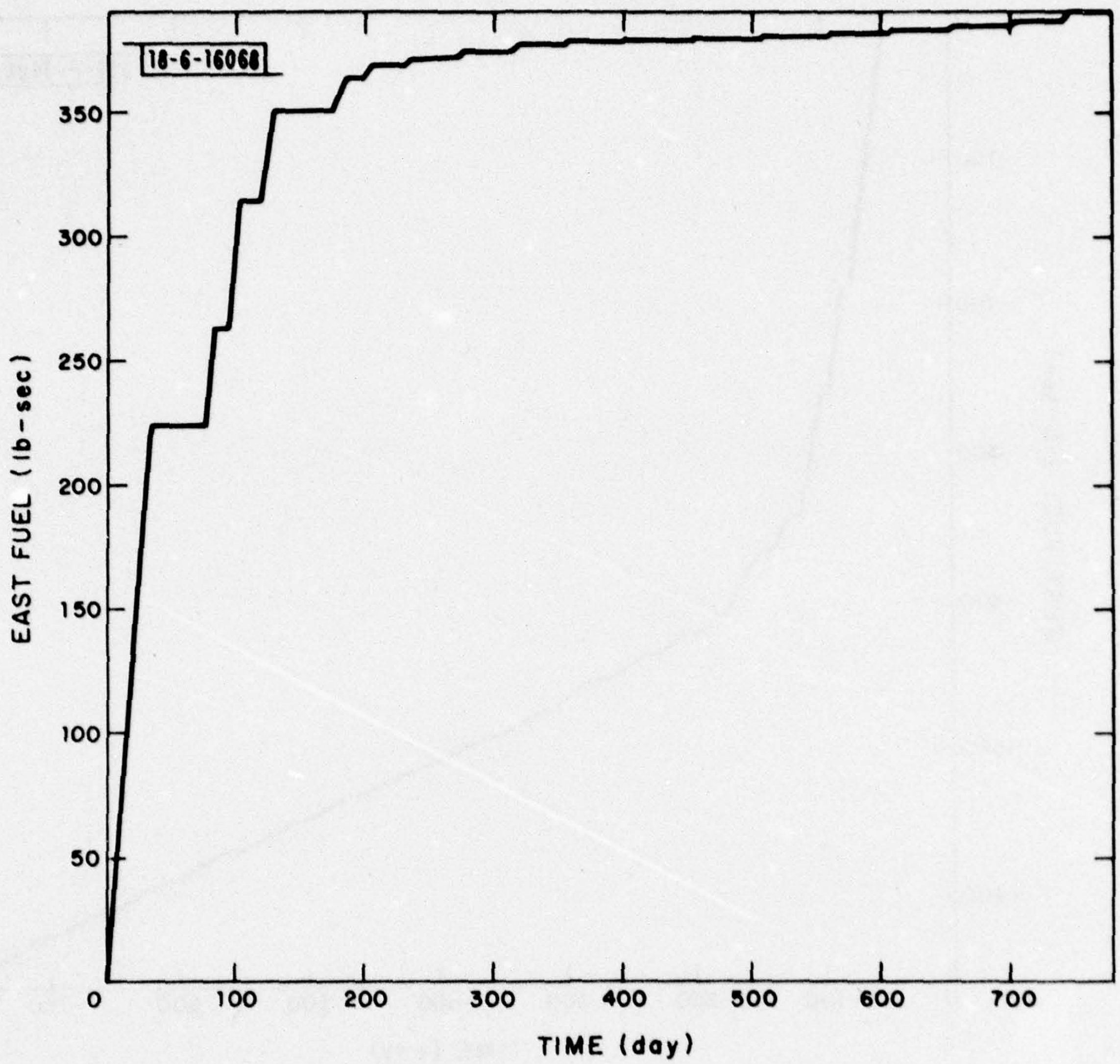

Fig. III-3. East fuel consumption vs. time during closed-loop testing on ground.

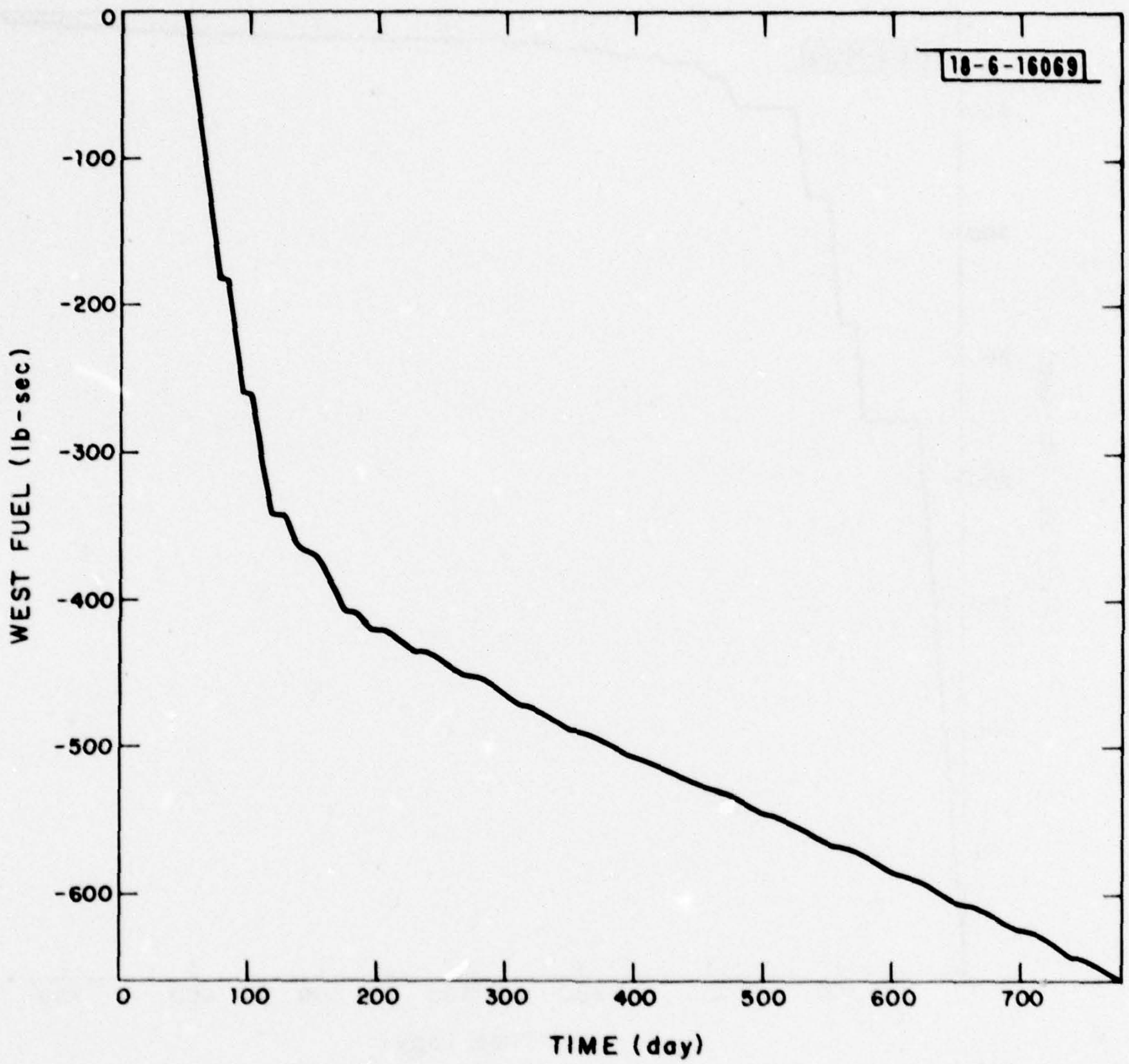

Fig. III-4. West fuel consumption vs. time during closed-loop testing on ground.

TABLE III-A

PRE-LAUNCH CLOSED-LOOP TESTING OF STATIONKEEPING SYSTEM[8]

Satellite mass (simulated)	1000 lb (mass)
Thrust level (simulated)	100 μ-lb (force)
Sensor mode	Sun transit
Filtering mode	8th-order
Geopotential acceleration (λ = drift from station)	$1.0 \times 10^{-5} \cos 2\lambda\ a_s/d_m^2$*
Controller Parameters:	
Damping constant	0.0625 day
Saturating drift	3.39°
Coasting speed	0.946°/day
Navigation Error:	0.05° rms (white gaussian)
Initial Conditions:	
Radial drift	$x_1(o) = 0.00\ a_s$
Radial velocity	$x_2(o) = 0.00\ a_s$/day
Angular drift from station	$x_3(o) = 60.0°$
Angular drift rate from station	$x_4(o) = 0.00°$/day
Performance:	
Settling time to station	140 days
Fuel consumed in station change	350 lb (force)-sec east 380 lb (force)-sec west
Stationkeeping accuracy	±0.15°
Steady-state fuel efficiency	86%

* a_s = mean semi-major axis of a geosynchronous satellite orbit, 42, 164.3 km

d_m = mean solar day = 86,400 sec

TABLE IV-A

PARAMETERS FOR TEST OF LES-8 STATIONKEEPING SYSTEM IN ORBIT

Operating Mode	Autonomous	
	Sun-Transit Sensor	
	Eighth-Order Filter	
	IR Pitch Sensor Enabled	
	Solar Ephemeris Enabled	
	Thruster Feedback Enabled	
	88-μ lb (force) Thrust Level	
Station Setting	109.71°W includes equation-of-time (solar-ephemeris) offset and sensor bias	
Controller Constants	Damping Constant	0.0625 day
	Saturating Drift	3.394° (7 July to 6 August 1976)
		0.747° (6 August 1976 onward)
	Coasting Speed	0.088°/day
Solar-Ephemeris Synthesizer	Initial Time	181.5 day
	Ascending Node	114.66°
	Inclination (ecliptic)	5.23°
	Initial Ephemeris	-0.05626°

Performance of the system during this experimental phase is summarized in Figs. IV-1, 2, and 3. Figure IV-1 shows the longitude based on the PEP LES-THRUST model and using the orbit fits done on 2 and 6 July, and 6, 8, 12 and 13 October 1976. Longitude is defined as the average of the subsatellite longitude at the ascending and descending node crossings on a particular day. The satellite longitudes were obtained by using the actual thrusting history on the satellite during autonomous stationkeeping control. The thrust level, adjusted to satisfy the two boundary conditions obtained from the orbit fits done in July and October 1976, was 90.6 μlb (force) [nominally 88 μlb (force)]. These orbit data agreed with the orbit measurements taken by the K-band terminal in Lincoln Laboratory. Figures 9 and 10 are based on the satellite orbit data.

Figures IV-4, 5, 6, 7 and 8 are based on on-board data. Figure IV-9 shows the fuel consumed during the test. System performance during operation in the overdamped mode was as follows:

Stationkeeping Accuracy	±0.06° (absolute) ±0.04° (rms)
Overshoots	None
Fuel Consumption	
Transient Mode (7 July to 14 August 1976, +0.15° off station)	92.24 lb(force)-sec east face 30.86 lb(force)-sec west face
Steady-State Mode (14 August to 4 October 1976)	17.79 lb(force)-sec east face 21.43 lb(force)-sec west face

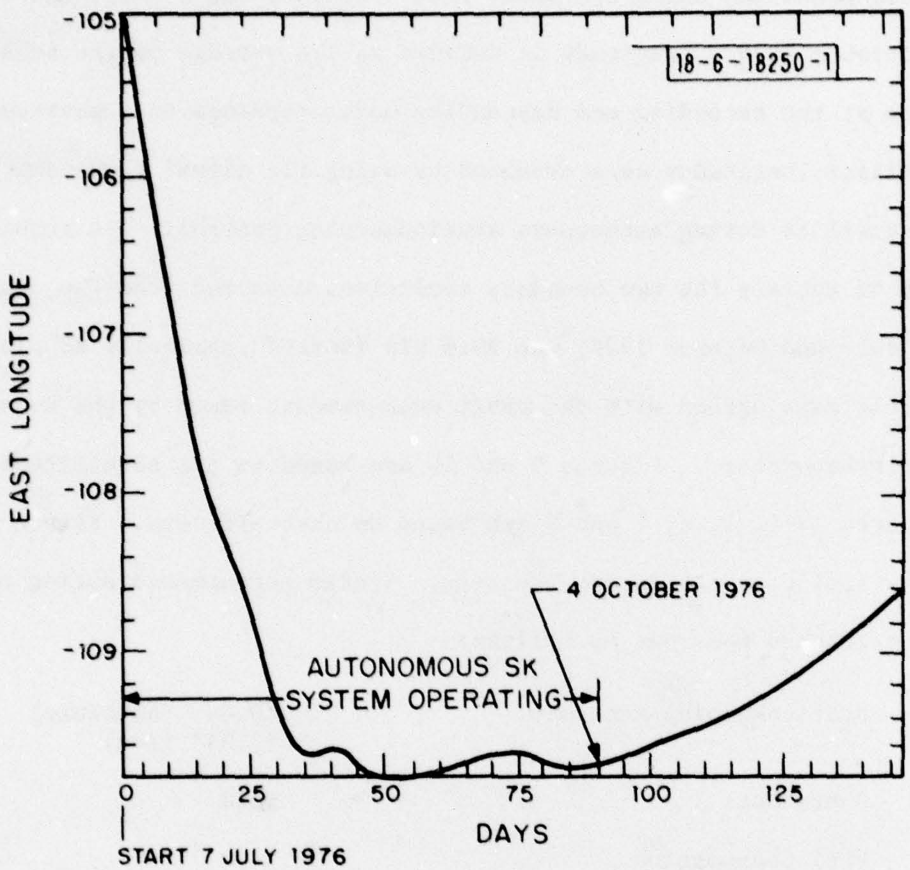

Fig. IV-1. LES-8 longitude based on ground observation data.

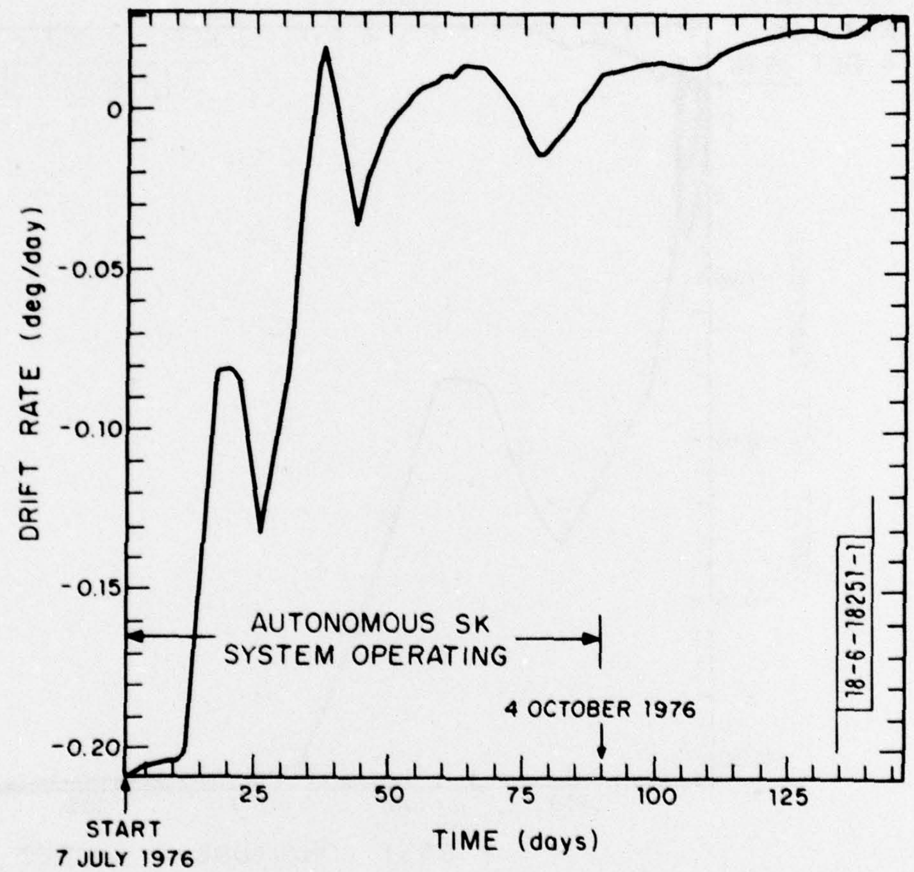

Fig. IV-2. LES-8 longitudinal drift rate based on ground observation data.

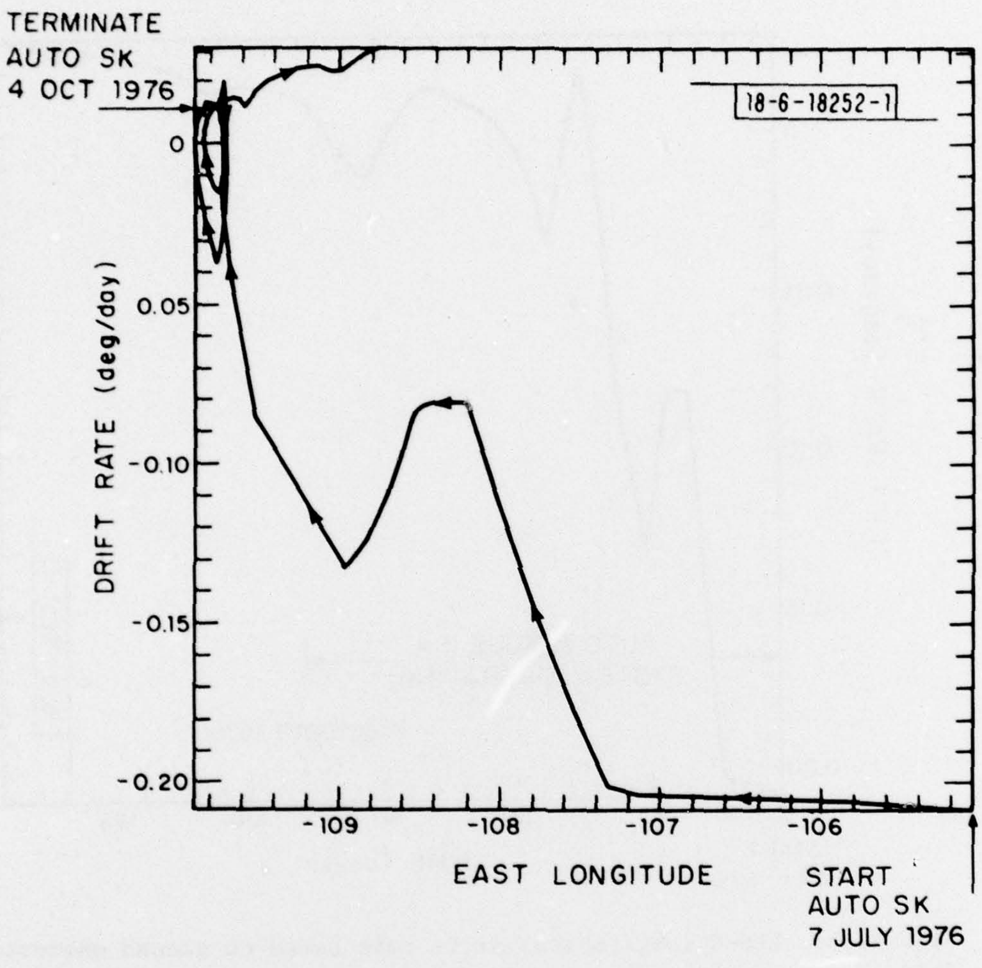

Fig. IV-3. LES-8 longitude vs. longitudinal drift rate based on ground observation data.

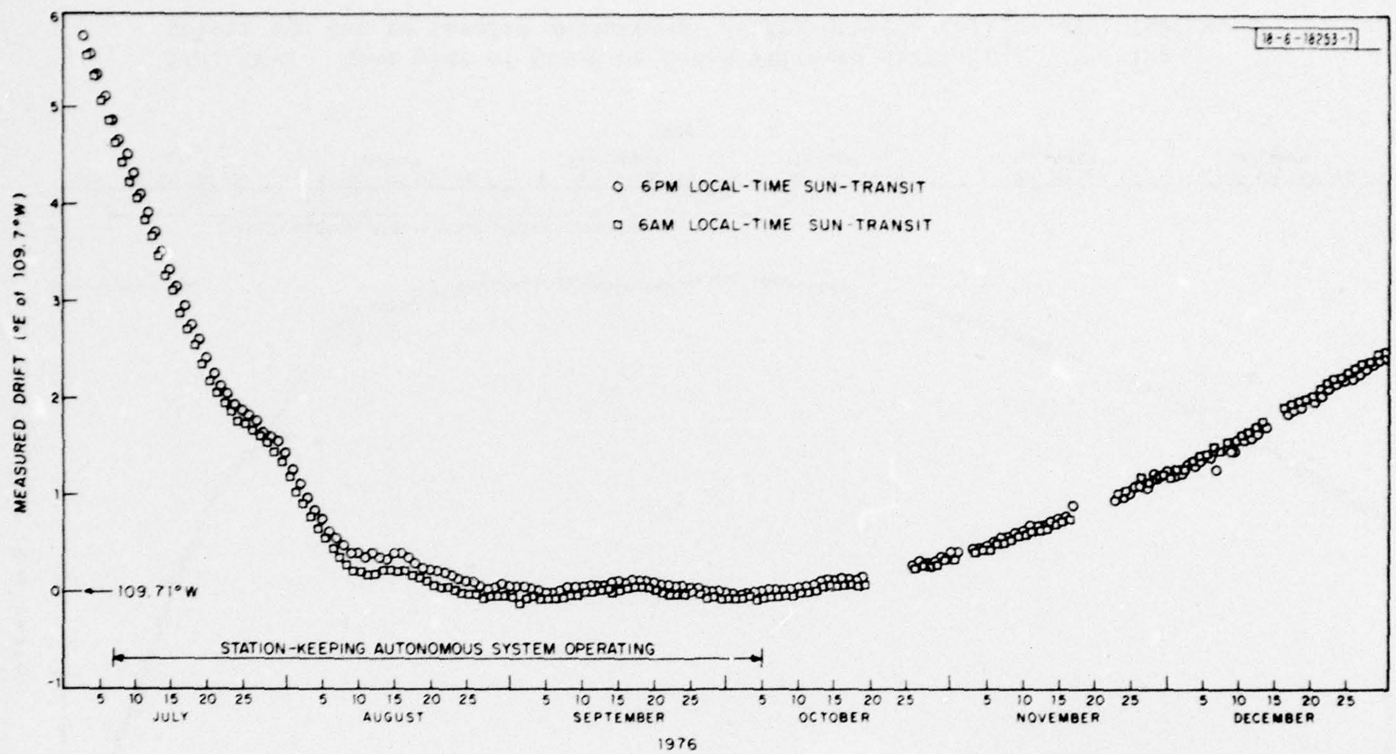

Fig. IV-4. Time plot of LES-8 on-board measured dirft (X_3). Missing points are due to invalid measurement during other satellite experiments.

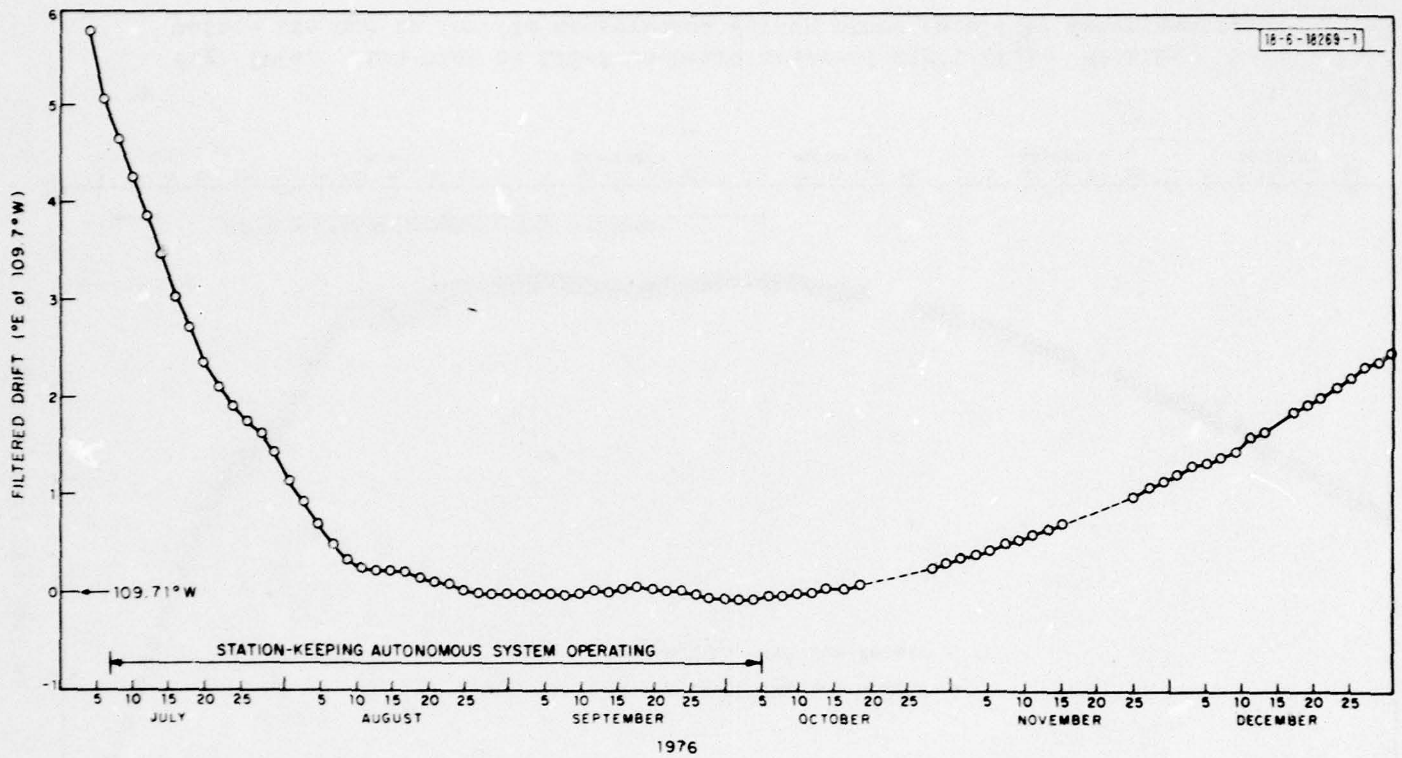

Fig. IV-5. Time plot of LES-8 on-board filtered drift (Z_3). Missing points are due to invalid measurement during other satellite experiments.

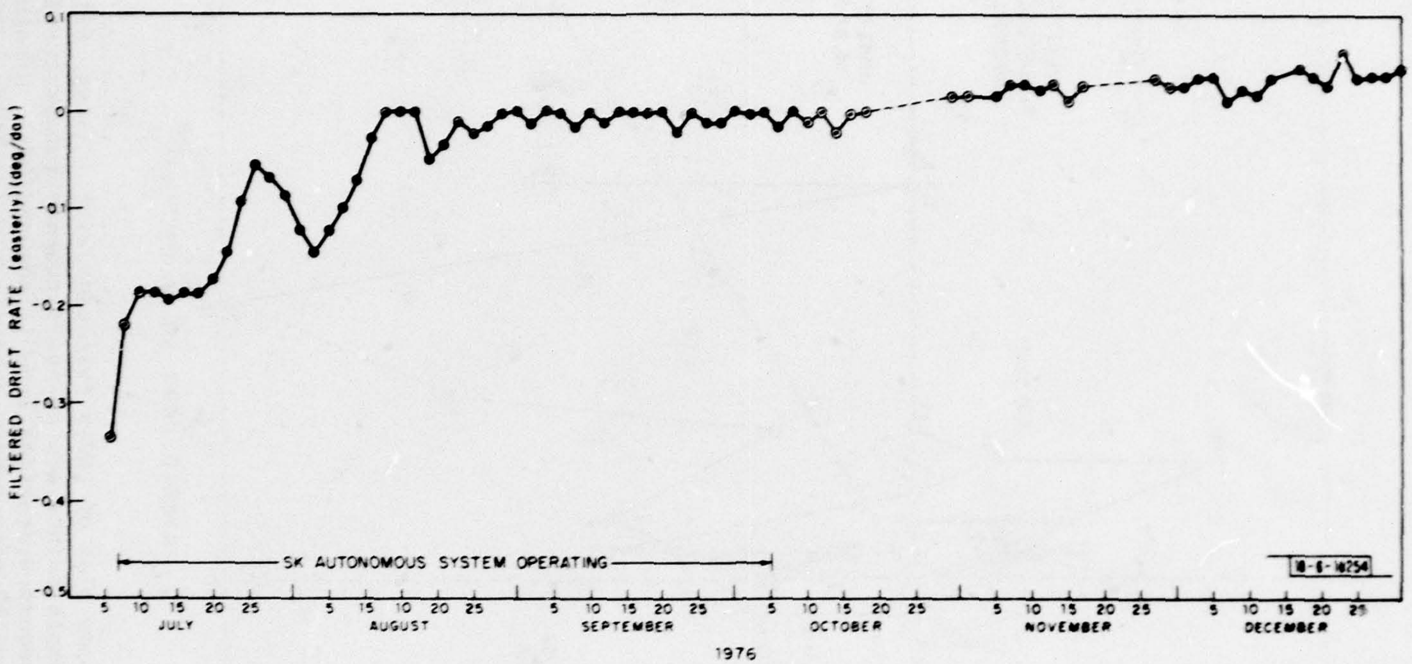

Fig. IV-6. LES-8 longitudinal drift rate computed on-board. Missing points are due to invalid measurement during other satellite experiments.

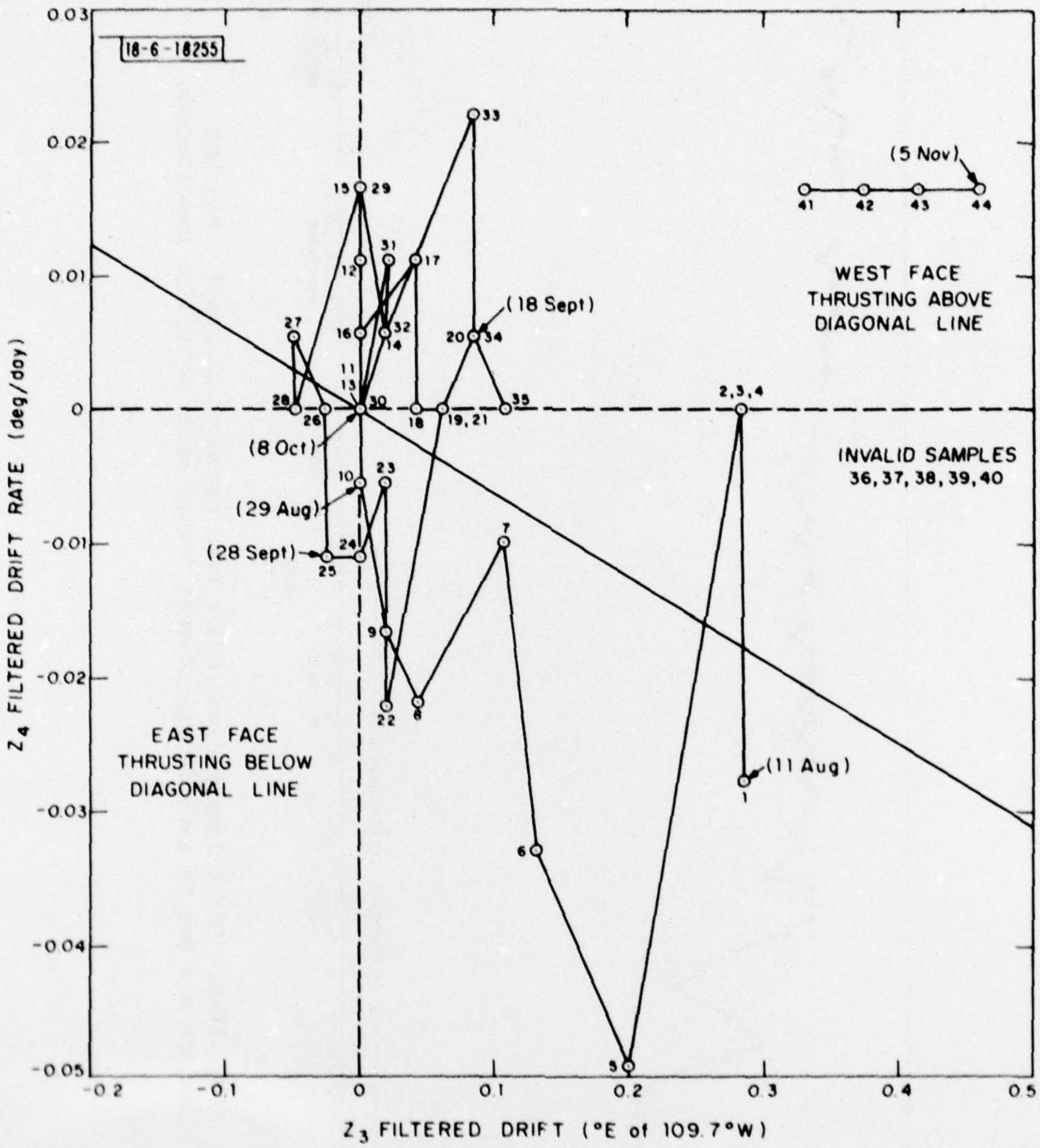

Fig. IV-7. Phase-plane plot of LES-8 filtered drift (Z_3) vs. filtered drift rate (Z_4). Sample points are at every two-day interval and shown in numerical sequence starting from 11 August 1976. Missing points are due to invalid measurement during other satellite experiments.

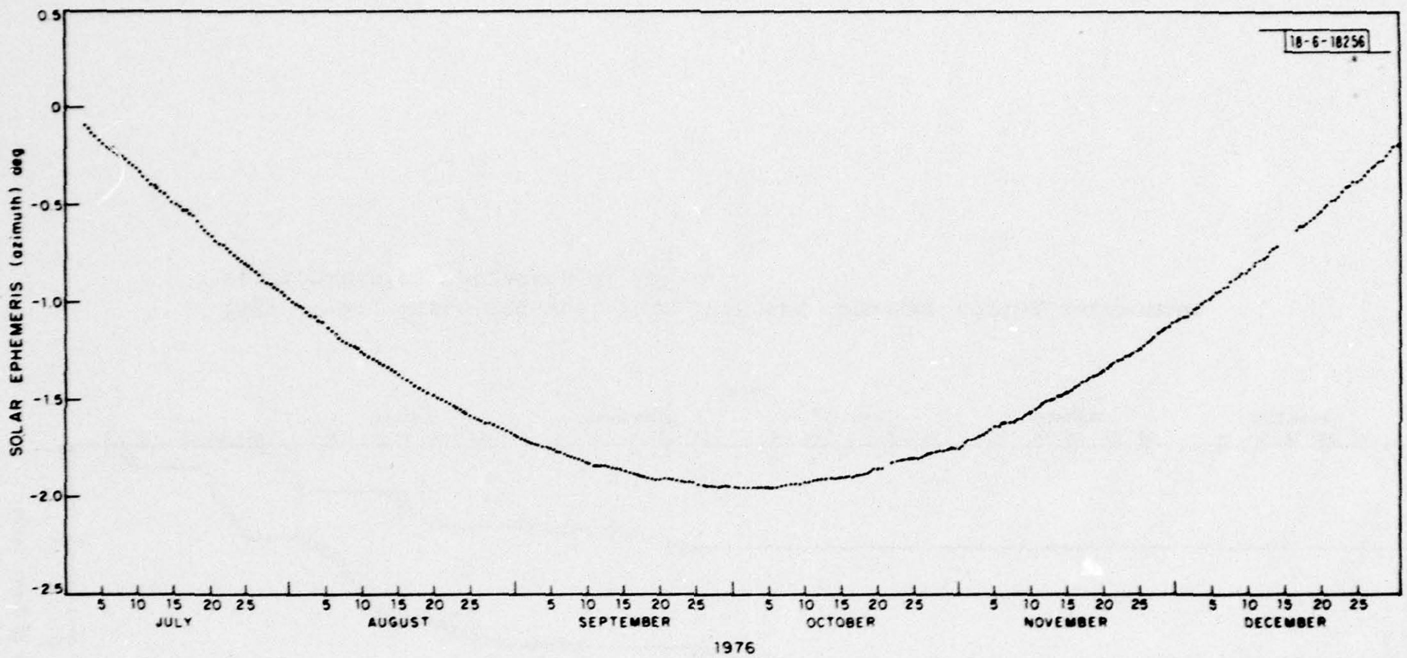

Fig. IV-8. Time plot of LES-8 solar ephemeris (azimuthal component) computed on-board. Missing points are due to invalid telemetry data.

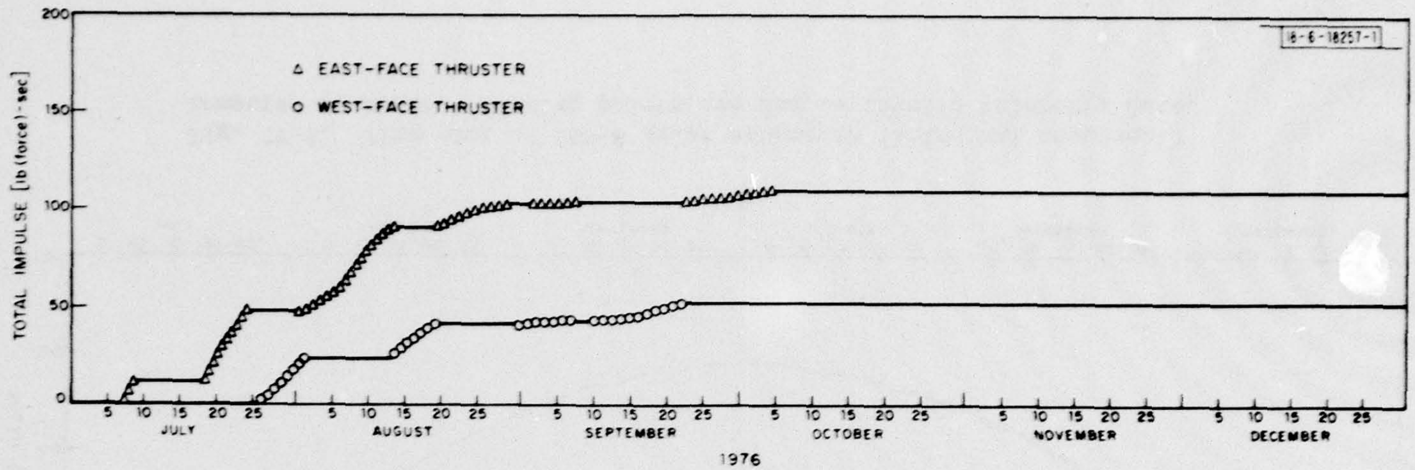

Fig. IV-9. East- and west-face thruster impulses during autonomous stationkeeping operation of LES-8.

V. FUTURE SYSTEMS

The flight results of the LES-8 autonomous stationkeeping system have shown that the satellite position can be measured on-board with an accuracy of at least 0.02° (rms). This measurement accuracy was sufficient to stationkeep the satellite to better than ±0.06°. The controller and the digital filters in the LES-8/9 stationkeeping system were limited to simple realizations due to power and weight constraints. This resulted in a design trade-off that yielded non-optimum transient response and fuel efficiency. In future satellites with the same power and weight constraints as LES-8/9, it should be possible to implement better filtering and controlling schemes (e.g., Kalman-type filters) and to obtain much higher fuel efficiency. For the same navigation error as LES-8/9, it should be possible to design the filter and controller to give better than 90% fuel efficiency.

Most future communications satellites are expected to carry central data-processors (computers) to perform various operations in a time-shared mode. The total computation required for the stationkeeping system is small and can be very conveniently done by the central data-processor along with its other processing tasks. All the other hardware that is used for stationkeeping (except the Sun-transit sensors) is necessary to perform other essential functions on the satellite, such as attitude control. Therefore, in most future satellites the stationkeeping function can be implemented with a minimal amount of hardware exclusively designated for the stationkeeping system.

The LES-8/9 satellites required east/west stationkeeping. Some geostationary satellites may require both north/south and east/west stationkeeping. The

principles of the east/west stationkeeping system demonstrated on LES-8/9 can be directly extended to implement the north/south ststionkeeping system for such future communications satellites.

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The author is indebted to many people for the work on the autonomous stationkeeping system reported in this note. The use of sun and earth sensors for computing satellite longitude was proposed by Walter E. Morrow in 1965. Alvise A. Braga-Illa designed the first autonomous stationkeeping system for the Lincoln Experimental Satellite 6 (LES-6). Donald C. MacLellan and F. Williams Sarles, Jr. introduced me to the problem; I am grateful for their continuous support and encouragement. Norman R. Trudeau and Bradford Howland designed the high accuracy sun-transit sensors. Franklin W. Floyd proposed the use of an earth shadow sensor. Franklin W. Floyd and Joseph R. Vernau procured and designed the propulsion system and the infrared earth sensing system. During the entire project, I had stimulating discussions with Roger W. Brockett on various aspects of the system. In particular, I would like to mention his work on modelling, observability and controllability of the system. William A. Petersen, Robert F. Williams, Alfred (Ken) O. Alves and Richard D. MacInnes gave valuable assistance during the design, construction and testing of various flight and ground hardware. Frederick S. Zimnock and William B. Smith did most of the computer simulation for design and ground testing of the system. Michael E. Ash's monumental and singular work on the planetary ephemeris program (PEP) was used for the satellite orbit determination and system evaluation. Leslie N. Weiner, Kenneth E. Virgile, Ronald J. Pelletier and Geoffrey T. Flanders did most of the simulation and data processing during the flight evaluation. William W. Ward helped in scheduling and conducting the flight experiment. I had many useful discussions on hardware design with Ervin S. Davis, John H. Helfrich and Paul F. McKenzie. Thanks are due to Jean C. Parsons and Sandra B. Clarke in putting this note together.

My sincere thanks to many other colleagues and co-workers, not specifically mentioned above, for their valuable help and suggestions during the analysis, design, construction, testing and evaluation of the autonomous stationkeeping system.

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This note is a summary of the initial flight results of the Lincoln Experimental Satellite 8 (LES-8) autonomous stationkeeping system. The autonomous stationkeeping system on LES-8 was activated between 7 July and 4 October 1976 for stationkeeping the satellite at 109.7°W longitude. The satellite acquired station without overshoot and maintained the station with an absolute accuracy of 0.06°. The fuel efficiency during this experiment in the overdamped mode was about 50%.

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